



Queensland University of Technology
Brisbane Australia

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Modeling Circulation of Train-Set with Multiple Routing

Abstract: Planning on utilization of train-set is one of the key tasks of transport organization for passenger dedicated railway in China. It also has strong relationships with timetable scheduling and operation plans at a station. To execute such a task in a railway hub pooling multiple railway lines, the characteristics of multiple routing for train-set is discussed in term of semicircle of train-sets' turnaround. In programming the described problem, the minimum dwell time is selected as the objectives with special derive constraints of the train-set's dispatch, the connecting conditions, the principle of uniqueness for train-sets, and the first plus for connection in the same direction based on time tolerance σ . A compact connection algorithm based on time tolerance is then designed. The feasibility of the model and the algorithm is proved by the case study. The result indicates that the circulation model and algorithm about multiple routing can deal with the connections between the train-sets of multiple directions, and reduce the train's pulling in or leaving impact on the station's throat.

Key words: railway transportation; train-set; scheduling; semicircle of trains' turnaround; multiple routing

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1 Foreword

Locomotives and rolling stocks are important vehicles, and the utilization and optimization of that can save the cost and improve efficiency for railway passenger transport. But the largest distinction between train-sets and the existing locomotives and rolling stocks is that the traction power of train-sets cannot be separated from the equipment used to carry passengers, so that the utilization and optimization of them will be different. The rationable connections between train-sets and optimally operation, for example, connecting train paths without a direction change at stations (especially at large hubs) wherever possible, will be important to fulfill the tasks specified on timetables and be also essential for stations to reasonably and efficiently receive and depart trains, and complete all running and shunting operations of trains.

At abroad, train-set operation for high-speed railways is often planned in combination with the running plans, timetables, and dispatching systems of passenger trains. Because the adjustment is made on the level of integrated dispatching systems to improve the utilization rate, reduce the utilized number and save the operating cost of train-sets. An example is in Japan, where through a Computerized Safety, Maintenance and Operation System of the Shinkansen (COSMOS), the management on the organization of train operation, including the carriage operation, has been completely computerized. In France, train-sets have been more efficiently utilized via a combination of long and short routing and multiple passes of cyclic running. But, in Germany, this has been achieved through excellent connections between train paths according to optimized timetables. In Holland, train-set connections have been preliminarily considered into timetable planning by scholars. The train-set operation has been broken down to turnaround planning and maintenance planning. The core of turnaround planning is addressing the coupling and break-up of train-sets, establishing an integer programming model, and reaching a solution with simulation software. Gábor Maóti (2006) reported a detailed analysis on the Dutch planning phases, namely, strategic planning, tactical planning, operational planning, and short-term planning. A tactical rolling stock scheduling model and a short-term maintenance planning model were created for train-sets. Moreover, the models were proven to be feasible in some railway cases in Holland^[1]. Marc Peeters (2006)^[2] and Arianna Alfieri (2006)^[3] suggested rolling stock scheduling models for train-sets on multiple correlated routes and a single route, respectively. To maximize the utilization of train-set units, train-set coupling and break-up were examined. When a train-set has fulfilled traction tasks for a certain mileage, it will be subjected to maintenance. Gábor Maóti and Leo Kroon proposed a transition model^[4] (2005) and an interchange model^[5] (2007) for

train-set maintenance planning based on the complexity of input conditions.

After many years of operating history of high-speed railways at abroad, timetable planners have begun to preliminarily consider the connection between train-sets. Station operation planning has been rather sophisticated due to years of improvement in western European countries. In addition, periodic timetables were normally adopted by foreign high-speed railways operators to guide their operation. This, to some extent, reduces the scale of the question. Therefore, whether these research achievements are suitable to China's newborn practice of transport organization along dedicated passenger lines should be examined.

Domestic experts focus on studying the optimization objectives such as train-set quantity, maintenance period, and maintenance balance and derive the train-set utilization programs that can fulfill the given train operation tasks on the conditions that given train-sets on the types, quantity, carrying capacity, and maintenance period of given train-sets, capacity of maintenance sites, and other operational conditions. Many experts have carried out research on the operation methods^[6], maintenance modes^[7] and operation of train-sets. It is reported that a better operational method of train-sets in China is to choose not to fix their operational sections^[8]. This method has been the basis for many experts to create models for train-set operation questions and reach solutions. Lan Shumei (2002) studied the train running programs on the Beijing-Shanghai High-speed Railway and suggested a circular routing mode without fixing the operational section for high-speed train-sets^[9]. Circular routing refers to that a high-speed train-set should be brought to the nearest depot for maintenance after leaving a depot and running for a specified maintenance mileage in several return trip operations in one or more directions. Nie Lei *et al* (2001) studied train-set operation based on the timetables of unpaired high-speed trains, and created a model that considered the return trip with empty wagons, maintenance duration, and other constraints^[10]. Based on the transport of Japan's high-speed railways at that time, Zhao Peng *et al* (2004) managed to improve the efficiency of reaching satisfactory solutions by pre-assigning connections for maintenance, and suggested a greedy algorithm based on probabilistic local search^[11]. Also at the period, he studied the algorithm for multi-base train-set operation planning based on railway section interchange^[12]. Tong Lu *et al* (2009) created a train-set operation model targeted at minimal and balanced utilization of train-sets, and reached solutions with their designed ant colony algorithm. Mao Baohua *et al* (2009) became the first researcher who had tapped the integrated railway operation planning to suggest a dual-layer optimization model for operation programming, train operation planning, and crew turnaround planning, in order to improve the enforceability and general optimization level of the operation plans. However, most of the above studies have been based on the existing timetables. Generally, they did not consider how the throat of a station can be affected by train-sets entering and exiting the same station. In addition, most of the existing studies were based on a certain route rather than the hub-based multi-routing train-set operation among multiple routes.

Studying a "Semicircle of Train's Turnaround" (STT)-based multi-routing train-set turnaround model is important significance to mitigate the effect of station entry and exit of trains at station throats. In this paper, the author examines the research achievements at home and abroad, and suggests the STT concept to address hub-centered multi-routing train-set turnaround. In addition to analyzing the characteristics of such turnaround, the paper creates a hub-based multi-routing train-set turnaround model. A concept of time tolerance σ is proposed to reduce the connections between train-sets with direction change at hubs, and

mitigate the effect that the frequent throat-cut resulting from the entry and exit of train-sets may impose on the train-reception and -departure at stations.

2 Characteristics of Multi-routing Train-set Turnaround

Multi-routing train-set turnaround is essentially about to study a STT-based train-set operation method. STT refers to a train-set starting from a hub and ending at a terminal station (the arrival station of a route) to always follow circular routing by undertaking return trip operations in multiple directions, and a train-set ending at a hub to return or not depending on the connection constraints between train-sets. STT-based multi-routing train-set turnaround has the following characteristics:

(1) With a special timetable planning mode, connections between train-sets are considered only if they occur at hubs.

The STT-based train-set turnaround mode must combine with a special method of timetable planning. After train-set arriving at its arrival station from a hub and satisfied with the minimum connection condition, the train-set carriage should immediately return to the same hub; As such, a return trip operation in one direction is realized. Therefore, optimizing the connections between train-sets at hubs is the key in a STT-based train-set turnaround mode.

(2) Connections between train-sets should avoid direction change whenever possible.

Train-sets can immediately return at a station through connections with or without a direction change. As defined in this paper, a connection without a direction change refers to the process all through which the station throat is not longitudinally cut by any activity that may occur since a train-set enters the station along one path until it departs from the station along the next path. See Figure 1 for details.

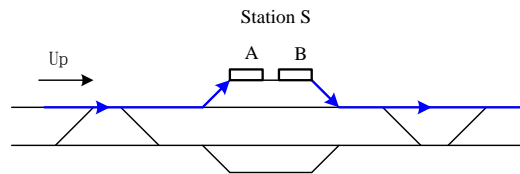


Fig. 1 Connection between trips without a direction change

In Figure 1, station S is where train A arrives at, train B departs from, and both trains are connected to each other along a train path indicated by the arrows. From the arrival of train A to the departure of train B, the carriages do not cut the throat longitudinally, nor do they interfere with the parallel operation on the reception and departure yard underneath. Therefore, we say that the connection between train A and B is free from a direction change.

A large passenger hub usually connects multiple directions and the trains in these directions can interfere with one another in the throat. That is to say, the trains that can enter, pass, or exit the station in one direction per unit time are restricted by those in any other direction. Especially, the throat is always cut if a hub is so arranged that trains are received without a direction change but depart with a direction change, or received with a direction change but depart without a direction change. This considerably affects train operations in the other direction. Therefore, in addition to considering the station layout, the STT-based multi-routing train-set turnaround method should also enable train paths to connect to each other in the same direction without longitudinally cutting the throat; that is, the train-sets should be connected to each

other without a direction change wherever possible.

(3) A multi-routing train-set turnaround question of a large-scale railway network can be broken down into multi-routing train-set turnaround questions in small-scale railway networks based on several hub-centered.

Studying the train-set turnaround question in a large-scale railway network, which usually consists of multiple hubs, will enlarge the question scale. Moreover, The enforceability of the train-set turnaround plan will be effected. Therefore, a large-scale railway network should be divided into multiple sub-networks, for each of which a hub-centered train-set turnaround model should be created.

3 Multi-routing Train-set Turnaround Model

The core of train-set operation planning has two parts that one is to fulfill timetable tasks and second is to make train-set maintenance. The first part is mainly to improve the operating efficiency of train-sets by connecting them to one another in a reasonable manner, and the second part mainly consider to ensure their excellent operating performance through maintenance at an appropriate site after they have accumulatively operated for a certain time or distance. This paper mainly studys the connection between STT-based multi-routing train-sets and examines their connections at hubs. Train-set maintenance is not covered.

To facilitate our description, the following variables are defined herein:

i -- A train path in the railway network. $i \in N$, N is the set of train paths in the railway network.

S , S_h -- a station and a hub in the railway network, respectively. $S^h \subset S$;

n_{as} , n_{ds} -- the numbers of train paths arriving at and departing from station s , respectively, $s \in S$;

a_i^s , d_i^s -- the instant when train path i arrives at and departs from station s , respectively;

S_i^a , S_i^d -- the arrival station and departure station of train path i , $S_i^a, S_i^d \in S$;

x_{ij}^s -- a decision-making variable defined in formula (1):

$$x_{ij}^s = \begin{cases} 1, & \text{Train's route } i \text{ and } j \text{ are connected at station } s \\ 0, & \text{Others} \end{cases} \quad (1)$$

C_{ij}^s -- the time standard for the connection between train path i and j at station s . It is the transition time from the instant when a train-set completes the previous train path i to the instant when it begins the next train path j , and is affected by the station layout, number of passengers, and train-set performance;

T_{ij}^s -- the assignment expense, i.e., the dwell time of a train-set for turnaround at station s . It is defined in formula (2):

$$T_{ij}^s = \begin{cases} d_j^s - a_i^s & (d_j^s - a_i^s \geq C_{ij}^s) \\ 1440 + d_j^s - a_i^s & (d_j^s - a_i^s < C_{ij}^s) \end{cases} \quad (2)$$

A -- the set of connection arcs between train paths;

A_h^s -- the set of connection arcs without direction changes at the hub. If train path i and j are connected to one another without a direction change, $(i, j) \in A_h^s$;

A_h^n -- the set of connection arcs with direction changes at the hub. If train path i and j are connected to one another with a direction change, $(i, j) \in A_h^n$;

SXC, NXC – total connection numbers with and without direction changes at the hub.

3.1 Object Function

The optimized objective of train-set operation plans has the following four categories:

(1) Minimal train-sets in operation to fulfill timetable tasks ^[6]

A minimized total dwell time of all train-sets for turnaround connections at stations leads to highest turnaround efficiency and minimal number of train-sets required, and therefore, corresponds to the minimal train-sets in operation that can fulfill timetable tasks.

(2) Minimal travel mileage of train-sets ^[1]

The operating expenses of a train-set include the expenses of the energy consumed for traction and the expenses of maintenance. If train-set travel mileage is minimized by avoiding or reducing travels with empty wagons, the expenses can be largely saved; provided that the operation tasks are fulfilled.

(3) Minimal short ratio of seats

Carriage seats are often insufficient to meet the demand in peak hours or special holidays, although they are always more than needed in normal operation. This gap of supply can be practically addressed by allowing coupling or break-up operations or replacing carriages of train-sets in addition to running more trains in special holidays. The degree of seat shortage is often represented by the short seats-km.

(4) Minimal coupling and break-up operations

Although coupling and break-up operations are acceptable at specific stations if the transport organization permits such operations, they do result in additional station shunting, affect the operation of other trains in the same station, and can result in train delays. Therefore, the organization should include minimal coupling and break-up operations.

In this study, the objective function is defined as the minimized total dwell time of all train-sets for turnaround connections at stations, although it has been chosen as the balance degree of train-set operation by some experts and scholars ^[13]. See Formula (3):

$$F^s = \min(\sum_{i=1}^{n_{ds}} \sum_{j=1}^{n_{ds}} T_{ij}^s x_{ij}^s), \text{ where, } s \in S \quad (3)$$

3.2 Constraint conditions

The connection conditions of train-set turnaround questions are classified into following three categories ^[14]:

(1) Running condition

A train-set must be located at the departure station of its responsible trip. Its earliest permissible running instant should be earlier than the planned departure instant of the trip.

(2) Connecting condition

The time from the instant when a train path is completed to the instant when the next path begins should not be less than the connection time standard between the two paths.

(3) Uniqueness condition

After a train-set undertaking the task of a train trip and arrives at a station, it can be utilized for only one train trip at one instant. In addition, the transport task on a train trip at a station can be undertaken by only one train-set at an instant. Moreover, the type of train-set and marshalling operation should be same for the trains required to be connected to one another.

Because the above constraint conditions does not consider how the train-set connection at a station can affect the throat at the same station, this paper introduces a concept of time tolerance σ . If all the arrival path i and departing paths j and k satisfy the connection condition at hub s , and they belong to the most compact connections with and without a direction change, respectively, the compact connection between path i and j without a direction change is prioritized when $d_j^s - d_k^s \leq \sigma$. Therefore, σ is introduced to make the most parallel operations available in the throat when the reception and departure tasks are fulfilled at the station. Its value is dependent on the station topology, the time difference between connections with and without a direction change, the response time of station equipment, and the unlocking methods of track circuits.

3.3 Mathematical Model

Using the aforementioned objective function and the connection constraint between train paths, the STT-based multi-routing train-set turnaround model, M1, is described as follows:

$$\begin{aligned}
 F^s = \min & \left(\sum_{i=1}^{n_{as}} \sum_{j=1}^{n_{ds}} T_{ij}^s x_{ij}^s \right), \text{ where } s \in S, (i, j) \in A \\
 \text{s.t. } & T_{ij}^s \geq C_{ij}^s \\
 & S_i^a = S_j^d \\
 & \sum_{i=1}^{n_{as}} x_{ij}^s = 1, j = 1, \dots, n_{ds} \\
 & \sum_{j=1}^{n_{ds}} x_{ij}^s = 1, i = 1, \dots, n_{as} \\
 & x_{ij}^s \in \{0, 1\}, i = 1, \dots, n_{as}, j = 1, \dots, n_{ds} \\
 & x_{im}^s = 0, x_{ik}^s = 1, \text{ if } d_k^s - d_i^s \geq C_{ik}^s, d_m^s - d_k^s \leq \sigma, (i, m) \in A_h^n, (i, k) \in A_h^s, s \in S^h
 \end{aligned}$$

3.4 Model Solution

Based on the description of the question, this paper designed a time tolerance σ -based compact connection algorithm, whose procedure is as follows:

- (1) Initialize the procedure by letting $x_{ij}^s = 0$;
- (2) Trains arriving at and departing from station s are separately sorted by the arrival time and departure time. This outputs an arrival chain list A and a departure chain list B. The lists contain the train-set types, train number, departure station, departure time, arrival station, and arrival time;
- (3) Select element i from chain list A, and element j from chain list B that satisfies $d_j^s - a_i^s > C_b$ and any $d_{j+m}^s \geq d_j^s, m = 1, \dots, n_{ds} - j$. If the connection between element i and j is free from a direction change, set $x_{ij}^s = 1$ and let $i = i + 1$, and mark the corresponding trains as being connected; otherwise, go to step (4) or, if $i = n_{as}$, to step (5);
- (4) For element i in the chain list, keep searching all elements following element j in the list. If the

connection between element i and element $j+m$, ($1 \leq m \leq n_{ds} - j - 1$), is free from a direction change, and $d_{j+m}^s - d_j^s \leq \sigma$, set $x_{i(j+m)}^s = 1$ and mark the corresponding trains as being connected; otherwise, set $x_{ij}^s = 1$, let $i=i+1$, and go to (3); and

(5) Search chain list A and B once again. Any train without a connection mark should be sent back to the depot if it is in chain list A or dispatched out of the depot for connection if it is in chain list B. The connection results are outputted.

4 Case Study

Assume a railway network as shown in Figure 2. A is a hub equipped with a train-set depot. B, C, D, and E are terminal stations with trains running to and from hub A. Use BA to indicate a path from station B to A, and AC to indicate a path from station A to C. Accordingly, there are paths DA, AE, CA, AB, EA, and AD in this network. According to the characteristics of connections without a direction change, BA and AC, CA and AB, DA and AE, and EA and AD are connections without a direction change while all other connections are those with a direction change in the network.

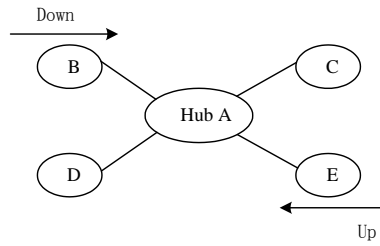


Fig. 2 Simple plot of a railway network

If the train-set turnaround is to be planned based on a timetable, all we need to know are the departure station, arrival station, departure time, and arrival time of each train. Assume a periodic timetable of the network as shown in Figure 3:

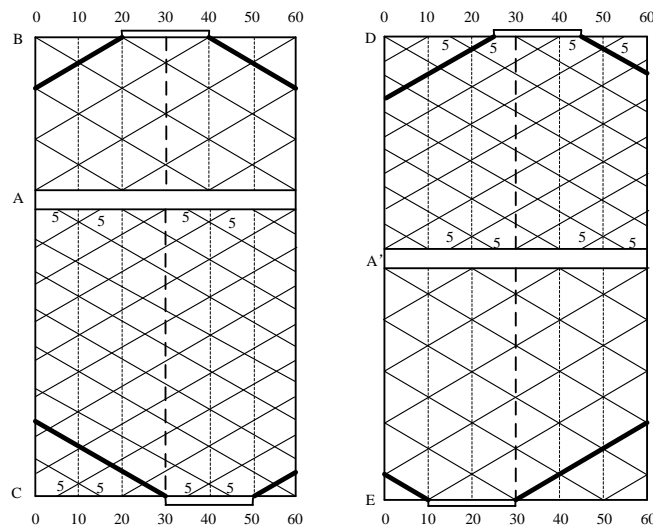


Fig. 3 Periodic timetable of the railway network

In Figure 3, the horizontal axis is the time and the vertical axis is the distance between stations. A (A'), B, C, D, and E are station names. The figure also indicates that three pairs of trains run between station A

and B in one hour, with a 60-minute running duration per train and a 20-minute departing interval. However, the trains running between station A and C, A and D, and A and E are 4 pairs (with a 115-minute running duration per train and a 15-minute departing interval), 4 pairs (with a 85-minute running duration per train and a 15-minute departing interval), and 3 pairs (with a 90-minute running duration per train and a 20-minute departing interval). According to the timetable, a train starting from hub A will immediately return after it arrives at the terminal station B, C, D, and E, with the returning time of 20 minutes, as illustrated by the bold lines in the figure.

Assume $\sigma = 5$ min, $C_{ij}^s = 15$ min, and all trains in the network are towed by the same type of train-sets. According to the periodic timetable illustrated in Figure 3, there are 27 pairs of trains that may be involved in connections at hub A from 9:00-11:00.

If the σ -based priority condition for connections without a direction change is not considered, model M1 is an assignment question and its solution outputs $F^A = 510$. There will be 5 connections without a direction change among of the connections between the 26 pairs of paths, and 2 out of these 5 connections will last for 15 minutes for each.

If the σ -based priority condition for connections without a direction change is considered, the model M1 can be solved using the σ -based compact connection algorithm. Thus, the objective function value so obtained will be $F^A = 510$. See Table 1 for the specific connections between the paths.

Table 1 Connection result of train-sets in hub A

Arriving at Hub A			Departing from Hub A			Connection Type	Connection Duration
No.	Departure time	Arrival time	No.	Departure time	Arrival time		
BA4	8:00	9:00	AC10	9:20	11:15	Direction unchanged	20
CA1	7:05	9:00	AB8	9:20	10:20	Direction unchanged	20
EA2	7:30	9:00	AD10	9:15	10:40	Direction unchanged	15
			AE8	9:20	10:50	From train-set depot	
DA4	7:45	9:10	AD11	9:30	10:55	Direction changed	20
CA2	7:20	9:15	AB9	9:40	10:40	Direction unchanged	25
BA5	8:20	9:20	AC11	9:35	11:30	Direction unchanged	15
EA3	7:50	9:20	AD12	9:45	11:10	Direction unchanged	25
DA5	8:00	9:25	AE9	9:40	11:10	Direction unchanged	15
CA3	7:35	9:30	AC12	9:50	11:45	Direction changed	20
BA6	8:40	9:40	AC13	10:05	12:00	Direction unchanged	25
DA6	8:15	9:40	AE10	10:00	11:30	Direction unchanged	20
EA4	8:10	9:40	AD13	10:00	11:25	Direction unchanged	20
CA4	7:50	9:45	AB10	10:00	11:00	Direction unchanged	15
DA7	8:30	9:55	AE11	10:20	11:50	Direction unchanged	25
BA7	9:00	10:00	AC14	10:20	12:15	Direction unchanged	20
CA5	8:05	10:00	AB11	10:20	11:20	Direction unchanged	20
EA5	8:30	10:00	AD14	10:15	11:40	Direction unchanged	15
DA8	8:45	10:10	AD15	10:30	11:55	Direction changed	20
CA6	8:20	10:15	AB12	10:40	11:40	Direction unchanged	25

BA8	9:20	10:20	AC15	10:35	12:30	Direction unchanged	15
EA6	8:50	10:20	AD16	10:45	12:10	Direction unchanged	25
DA9	9:00	10:25	AE12	10:40	12:10	Direction unchanged	15
CA7	8:35	10:30	AC16	10:50	12:45	Direction changed	20
BA9	9:40	10:40				Back to train-set depot	
DA10	9:15	10:40	AE13	11:00	12:30	Direction unchanged	20
EA7	9:10	10:40	AD17	11:00	12:25	Direction unchanged	20
CA8	8:50	10:45	AB13	11:00	12:00	Direction unchanged	15

Note: Trains in all directions are numbered from 7:00. CA1 means the first CA route scheduled since 7:00. All other trains are numbered similarly.

The following conclusions can be derived from Table 1:

(1) Among of the 27 pairs of trains that may be involved in connections, 26 pairs are actually involved in connections. Path AE8 requires a train-set exiting the depot for traction, while the train-set towing path BA9 has to enter the depot.

(2) Among of the 26 pairs of trains that are actually involved in connections, 22 connections are free from direction changes, creating opportunities for more parallel operations at the stations and making it possible to receive or dispatch trains in multiple directions at the same time;

(3) Among of the 22 connections without a direction change, eight connections take 15 minutes for each (see the bolded cells in the table). These are the weak points of train-set connections because of their insufficient buffer time.

The obtained objective function value of the model is always 510, whether the σ -based priority condition for connections without a direction change is considered. However, when the objective value is the same, such a priority condition increases the connections without a direction change at hub A by 17; As a result, the throat cuts by train entry and exit are much reduced. Based on the distribution of the 26 connection time values, the robustness of train-set turnaround plans is affected by such a priority condition to some degree, and such robustness can be reduced as appropriately according to the highly punctual operation of high-speed railways as proven by foreign experiences.

If a station only receives and dispatches limited number of trains, it is under limited operating stress, and all the train operation plans can be completed whether or not the inter-path connections have direction change. In such a case, it is of limited significance to consider the multi-routing train-set turnaround model with priority over connections without a direction change. However, as the number of trains received and departing in a station increases, the operating stress of the station, especially the reception and dispatch stress in the throat, will be increased, and the multi-routing train-set operation with such a priority becomes important. For instance, train BA6, DA6, and EA4 have to be received simultaneously at 9:40. If the paths of these three trains are connected to their successive paths with direction change, and trains are received with direction change but depart without a direction change at the station, the departure operation at the station will be inevitably affected at 9:40. When the number of received and departing trains further increases to a certain degree, the train operation plan will be less robust. Once a train is late, the multi-routing train-set operation will cause more severe train delays and the train operation plan is difficult to be recovered. Therefore, the multi-routing train-set turnaround model is more suitable to railway networks with dense distribution of trains.

5 Conclusions

The reasonable and efficient utilization of train-set can directly decide the high-speed railways to realize the state-of-the-art, safe, reliably, high-quality, and cost-effective transport demands. This paper:

(1) Proposes a STT concept, which requires a train-set starting from a hub and ending at a terminal station to always follow circular routing by undertaking return trip operations in multiple directions, and a train-set ending at a hub to return or not depending on the connection constraints between train-sets;

(2) Analyzes the characteristics of STT-based multi-routing train-set turnaround. The STT-based train-set turnaround method must work with a special timetable planning mode and the connections between train-sets will not be considered unless they occur at hubs;

(3) Introduces a concept of time tolerance σ . A σ -based constraint condition with priority over connections without a direction change is added to the model to minimize the total dwell time of train-sets at stations while the connections without a direction change are maximized; and

(4) Designs a σ -based compact connection algorithm to address train-set connections at hub A in a case study, which reveals that the throat cuts resulting from train entry and exit can be much reduced if the σ -based connections without a direction change are prioritized.

The operation question of train-sets consists of their turnaround planning and maintenance planning. This paper preliminarily analyzes the multi-routing train-set connections and designs a σ -based compact connection, from which a locally optimal solution is most possible and at the same time, maintenance planning is not considered. Further study is required on the train-set operation of networked dedicated passenger lines because the implementation of a turnaround plan depends on the station operation planning and the σ value cannot be determined without analyzing the station layout, route unlocking method, and releasing time of station equipment.

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References

- [1] Maóti G. Operations Research Models for Railway Rolling Stock Planning, Eindhoven, Technische Universiteit Eindhoven, 2006.
- [2] Peeters M, Kroon L. Circulation of Railway Rolling Stock: A Branch-and-Price Approach. Computers & Operational Research, 2006, 1–19.
- [3] Alfieri A, Rutger G, Kroon L, *et al.* Efficient circulation of railway rolling stock. Transportation Science, 2006, 40(3): 378–391.
- [4] Maóti G, Kroon L. Maintenance routing for train units: The transition model. Transportation Science, 2005, 39(4): 518–525.
- [5] Maóti G, Kroon L. Maintenance routing for train units: The interchange model. Computers & Operational Research, 2007, 34: 1121–1140.
- [6] Zhao P. Study on Motor Train-Set and Stuff Operation in High Speed Railway, Northern Jiaotong University, 1998.
- [7] Wu D. The Research of Train-Set Examination and Repair System Based on Operation, Beijing Jiaotong University, 2006.

- [8] Zhao P, Yang H, Hu A Z. Research on usage of high-speed passenger trains on uncertain railroad research. Journal of the China Railway Society, 1997, 19(2): 15–20.
- [9] Lan S M. Study on the relevant issues of train running program along Beijing-Shanghai high speed line. Railway Transport and Economy, 2002, 24(5): 32–34.
- [10] Nie L, Zhao P, Yang H, *et al.* Study on motor train-set operation in high speed railway. Journal of the China Railway Society, 2001, 23(3): 1–7.
- [11] Zhao P, Tommi N. An algorithm for train-set scheduling on weekday based on probabilistic local search. System Engineering-Theory & Practice, 2004, 24(2): 123–129.
- [12] Zhao P, Tommi N. An algorithm for multi-basestrain-set scheduling based on path-exchange. Journal of the China Railway Society, 2004, 26(1): 7–11.
- [13] Tong L, Nie L, Zhao P. Application of ant colony algorithm in train-set scheduling problem. Journal of Transportation Systems Engineering and Information Technology, 2009, 9(6): 161–167.
- [14] Mao B H, Wang B S, Xu B, *et al.* On integrated train operational scheme drawing-up platform of China. Journal of Transportation Systems Engineering and Information Technology, 2009, 9(2): 27–37.
- [15] Zhao P, Zhang J N. Review of railway train-set routing problem. Journal of Beijing Jiaotong University, 2009, 33(3): 6–10.